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Tailoring of acoustic phonon modes in mesoscopic devices is analyzed from the point of view of modifying and controlling deformation potential interactions.

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Tailoring Acoustic Modes in Mesoscopic Devices

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In numerous publications of the last several years [1,8], acoustic phonons have been quantized for a variety of nanoscale and mesoscopic structures in order to assess to role of electron--acoustic-phonon scattering in limiting the performance of nanoscale and mesoscopic electronic devices. These structures include quantum wells, quantum wires with cylindrical and rectangular cross sections, and quantum dots with spherical, cylindrical and rectangular boundaries. These quantized phonons have been studies for the two cardinal boundary conditions of classical acoustics: free boundaries (open boundaries) where the phonon displacements are unrestricted and allowed to balance all normal traction forces to zero; and clamped boundaries (rigid boundaries) where phonon displacements are required to vanish at the boundaries. For quantum wells, scattering rates have been calculated for free-standing structures [4,8]. For the case of quantum wires, scattering rates have been calculated only for the case of infinitely long quantum wires and, as appropriate for this case, the acoustic phonons have been quantized in only the lateral dimensions. However, for realistic mesoscopic device designs, the quantum wire input and output "leads" as well as the active regions of the devices with quantum-wire geometries have finite lengths. Accordingly, deformation and piezoelectric scattering rates must be based on acoustic phonons that are quantized in all three spatial dimensions. The international community does not appear to have considered the role of three dimensional confinement of acoustic phonons in mesoscopic devices but it is clear from the solutions of classical acoustics that boundary conditions imposed at the ends of wire-like regions can have a profound effect on the properties of acoustic modes. The results presented here are based, in part, on a consideration of the role of acoustic phonon confinement in mesoscopic devices containing finite wire-like regions. Based on our current understanding of such finite wire-like structures, we believe that it is possible to "engineer" mesoscopic structures so that electron--acoustic-phonon scattering is reduced. This reduction is likely to be most important in mesoscopic device which operate in the basis of "coherent" electron-wave interference effects.

In the domain of classical acoustics, especially revealing examples of the role of wire-like regions in modifying and tailoring selected acoustic mode patterns are those of the organ pipe and of the muffler. In the first example, the open boundary conditions at the ends of the organ pipe result in wave reflections with the reflected and transmitted waves having amplitudes with the same sign at the ends of the organ pipe. Subject to these boundary conditions, the acoustic modes in an organ pipe evolve so that standing wave amplitudes are maximized and anti-nodes are formed at the ends of the pipe; that is, the dominant modes are those having wavelengths such that the length of a half-integral number of wavelengths is equal to the length of the pipe. Thus, an organ pipe produces sounds at well defined and reproducible wavelengths. In the second example, a muffler suppresses sounds at exit ports through the use interfaces which produce modes with the required node and anti-node structures.

In the case of mesoscopic devices the situation is, perhaps, more complex than in the case of classical acoustic waveguides with open boundaries since, in general, the boundary conditions at the ends of the quantum wires require that both the mode displacements and the normal components of the stress be continuous. However, for the case of a quantum wire which couples to an "end" region composed of the same material as that in the interior of the quantum wire, the open boundary condition such be appropriate. Thus, for, example, in the case of a quantum wire with two "open" ends the ambient acoustic phonons in the wire will evolve so that the dominant modes are those having wavelengths such that the length of a half-integral number of wavelengths equals the length of the quantum wire. Just as in the organ pipe these modes will have their maximum amplitudes at the ends of the wires; that is, anti-nodes will be present at the ends of the quantum wire. Similar behavior may be expected for the case of free-standing quantum well structures. For the case of a quantum wire which couples to (or terminates on) a region composed of a material with acoustic properties different from those of the material in the interior of the wire, the exact boundary condition must, in general, be applied. From classical acoustics it is known that few analytical solutions are available for the cases where the complete boundary conditions must be used. A useful simplification arises in the case where the material in the interior of the quantum wire and the material at the end of the quantum wire have such different properties that the phonon modes are damped abruptly at he interface between the two materials; in this case, the so-called "clamped" boundary condition is adequate and the modes amplitudes may be assumed to vanish at such interfaces. Such a case applies at some metal-semiconductor interfaces. In particular, for a mesoscopic device having wire-like regions which terminate on a variety of metal regions (regions used as contacts, gates, barriers, etc.) it is satisfactory to apply clamped boundary conditions. At these boundaries, the acoustic modes will have nodes instead of the anti-nodes that are established in the case of an open boundary.

With this set of simplified boundary conditions it is possible to design mesoscopic structures with the phonons "engineered" to produce desired standing wave patterns. As an example, consider a four-terminal generalization of the three-terminal "tee"-shaped de Broglie wave interference device [9]. More specifically, consider a mesoscopic structure with quantum wires intersecting each other at right angles such that the two wire "centers" are at the same point. For this structure the ends of one wire are taken to be open and the ends of the other wire are taken to be clamped. Hence, it is possible to select some acoustic modes such that nodes will occur in "center" of one wire and anti-nodes will occur at the "center" of the other wire. By selecting various wire lengths it is possible to define a standing wave pattern that either maximizes or minimizes the amplitudes of specific acoustic phonon modes in regions where the electronic wavefunctions are dominant. Furthermore, by "engineering" interfaces within a quantum wire which are perpendicular to the quantum-wire axis, it should be possible to control the acoustic modes in wire-like regions of mesoscopic devices just as the classical acoustic modes are controlled in a muffler. Thus, the deformation and piezoelectric scattering rates may be partially tuned by tailoring the ambient phonon standing wave patterns in such mesoscopic structures.

In this effort to "engineer" the ambient phonon modes, the quantum-wire phonon modes obtained previously [1,8] should correctly describe the lateral quantization of the phonon modes. Elementary examples of such effects are implicit in the results of Ref. [8]. The quantization along the lengths of the quantum wires will be treated approximately under the simplifying "open" and "clamped" boundary conditions to assess the extent to which mesoscopic device properties may be controlled through the "engineering" of the phonon modes in mesoscopic devices. It is emphasized once again that the major payoff from the "quantum engineering" of acoustic phonons in quantum wires is the reduction of electron--acoustic-phonon scattering and the consequent preservation of "coherent" electron waves in mesoscopic devices. Achieving nearly-coherent electron waves may ultimately depend sensitively on reducing electron--acoustic-phonon scattering even though such processes may be considered to be weak by normal standards.

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